Infrared processing equipment for the food industry

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Chapter outline head

3.1 Introduction

Keeping fresh characteristics of fruits and vegetables while assuring adequate and suitable shelf life is one of the main goals of food preservation and processing methods. These methods must also assure maintaining the nutritional value and safety of processed foods. Food processing methods include a wide range of processes and technologies that improve the quality and stability of the foods, maintain the fresh-like characteristics or minimize their changes, as well as inactivate microorganisms. Infrared (IR) heating is one of the relatively new technologies that offer several advantages under similar conditions in comparison with conventional heating techniques. These advantages include higher quality preservation, uniform heating pattern, simple, compact, and versatile equipment, shorter processing time, and substantial energy conservation. Conventional processing operations such as thawing, dehydration, freeze-dehydration, blanching, cooking, baking, and roasting, can be combined with IR heating, which has provided the food industry with new options for processing methods. In order to increase the energy throughput of thermal process-

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ing, in addition to IR heating, combinations of conventional convective and conductive heat transfer methods with microwave heating have become a novel area of research and development. Therefore, the number of patents and research articles published on this topic is increasing, which shows the potential of IR heating technology for use in diverse and novel applications in food processing (Rastogi, 2012).

IR radiations have specific radiative properties comparable to other electromagnetic waves such as radio frequencies and, microwaves (Fig. 3.1). In the design of IR heaters, energy intensity and spectral distribution are the two important radiative aspects that should be considered. The surface temperature of IR heating elements and appropriate optical filters can be used to control the IR radiation's spectral region. Different ingredients of the food can absorb IR radiation in different spectral regions. For example, proteins can absorb IR radiation in a constricted 6–11 μm spectral region. In addition, the moisture content of the food can affect the IR reflectivity of the surface as a decline in moisture content can increase the surface reflectivity and reduce IR absorptivity. It is very important to consider the above-mentioned optic-thermal engineering properties in food products as they undergo IR processing (Pan and Atungulu, 2010).

One of the oldest methods for the processing of foods is heating, which has been used by humans, for thousands of years. Although heating food is an ancient processing method, during the 20th century, this technology evolved dramatically and the methods used for thermal-processing of foods have progressed rapidly and this progress is still happening in the present days. Conventional heating technologies

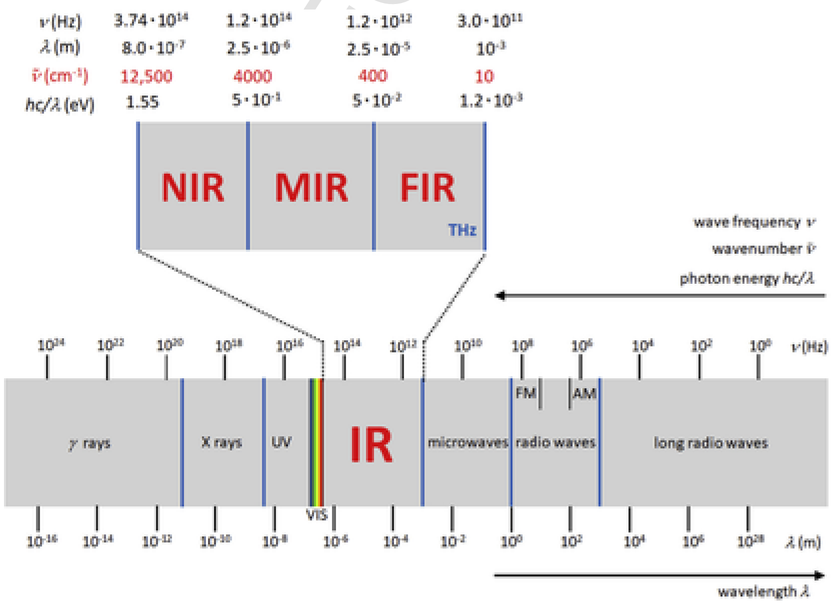

Figure 3.1 Infrared region in the electromagnetic spectrum (Bec et al., 2020).

mostly rely on conductive, convective, and radiative heat transfer while there are novel heating methods emerging such as inductive heating, radio frequency heating, microwave heating, and Ohmic heating where the heat is generated directly inside the material. Such novel heating technologies have the potential to be used as substitutes for conventional methods or in combination with them. The efficiency of heating, as well as energy efficiency, are affected by the heating method. IR heating is another heating method that can be used in food processing. There are also other novel food processing methods where the main processing factor is not an increase in temperature. They are called nonthermal processing methods that include gamma radiation, high hydrostatic pressure, ultrasound, high-intensity pulsed light, and pulsed electric fields. There might be a temperature change during such nonthermal processing methods as well, however, it is not the main processing element (Vicente, 2007).

As shown Fig. 3.1, the IR wavelengths electromagnetic spectra are allocated into three parts; far IR (FIR) with 4 μm to 1 mm wavelength (long waves), mid-IR (MIR) with 2–4 μm wavelength (medium waves), and near IR (NIR) with 0.7–2 μm wavelength (short waves). The NIR is emitted as the temperature reaches over 1000°C, while surface temperatures of 400°C or less emit the FIR. The MIR is emitted from the surfaces with temperatures between 400 and 1000°C. The electromagnetic spectrum of NIR, MIR, and FIR are shown in Fig. 3.1. In food processing equipment, IR heating has been used in many instances, as in ordinary ovens and several other conventional heating equipment, the FIR is the main radiative heat transfer mechanism. On the other hand, NIR heating is relatively new to the food industry applications. The main advantages of IR radiation heating are relatively easy to process control, quick response to adjustments, direct penetration into the food product with no heating of surrounding air, and high heat transfer capacity. These advantages can turn IR radiation into an ideal heating energy source as it has been used for the following applications:

- Baking pizza, biscuits, and bread, heating flour,
- Drying pasta, vegetables, rice, and fish,
- Roasting cocoa, coffee, and cereals
- Frying meat

IR heating can also be used for dry blanching, hybrid drying, surface pasteurization of bead and packaging materials as well as thawing the frozen products (Skjöldebrand, 2002; Vishwanathan et al., 2013).

In addition to thermal processing of food, IR portion spectrum can also be used in other ways such as noncontact measurement of temperature, and analytical applications namely spectroscopic measurement of chemical constituents known as Fourier-transform IR (FTIR) spectroscopy. One of the problems with IR heating of foods is that the penetration depth of the IR in the food materials' surfaces is usually low, yet choosing the right wavelength for some foods can increase the IR penetration depth significantly. Unlike opaque materials such as metals, in foods with semitransparent surfaces, the interaction with IR radiation is not just a surface property as the whole food bulk may interact with the thermal radiation. The interaction between IR radiation and foods can be different when various wavelengths are used. Therefore, the radiation properties of food materials depend on the food composition, IR wavelength, and other factors (Datta and Almeida, 2014).

In comparison with conventional heating, IR heating has significant advantages. These advantages include high energy efficiency, compact, simple and versatile equipment, uniform heating, shorter processing time, higher quality retention, and no nutrient loss due to leaching. This heating method can be used in different food processing methods, including, dry blanching, roasting, baking, drying, pasteurization, and sterilization. As IR heating has high energy throughput, combining it with other conventional conductive and convective heating methods, as well as novel heating methods such as microwave heating are becoming more popular. To design an optimized IR heating system, it is important to take into account the effect of IR radiation on the physical properties of food components. When a food surface is exposed to radiated electromagnetic energy, it can cause changes in the vibrational, rotational, and electronic states of the molecules. Food components absorb different IR wavelengths with different intensities. Same differences are observed for the reflection of IR radiation from food surfaces, for example under 10% of the radiation is reflected at the FIR wavelength region, while around 50% reflection occurs at the NIR wavelength region (Krishnamurthy et al., 2008).

Likewise, in the IR heating of fluid foods, IR radiation penetration depth is limited and the main thermal effect is occurred due to the warming of a thin liquid layer on the surface. The absorbed thermal energy is then transferred to other parts of the food material by convection and conduction. The conduction is inadequate in large volume samples, and therefore the total absorbed energy is lower in such samples. On the other hand, as this heating method mostly heats up the thin surface layer of the sample, cooling of the IR heated food is usually faster, and due to low thermal conductivity, less quality degradation is observed in the IR heated food materials. The penetrative radiation energy does not make a significant contribution to internal heating. Moreover, due to usually small sample depths, the convective currents are limited causing small flow rates. Thus, in the liquid samples, the thermal behavior of the food materials mostly correlated to external convective and radiative heat transfer on the top surface, and thermal conduction in the material (Rastogi, 2012).

3.2 Infrared emitters

Based on their wavelength, IR emitters are divided into three different categories, which are long-wave, short-wave, and medium-wave emitters. The effect of radiation on heated materials, heat transfer rate, and thermal efficiency are very dependent on the heating source wavelength range. Long-wave IR emitters can be used in low-temperature processes that require a combination of IR radiation and convective heating. Medium-wave IR emitters radiate an IR spectrum of 1.4–3.0 μm that could be used for curing and drying food products. Due to the possibility of overheating, the short-wave emitters may not be suitable for long thermal processing of food materials as they operate at very high temperatures, and emissive power (Pan et al., 2016).

Based on their primary energy source, IR emitters can also be categorized into gas burners and electrical types. Electrical IR emitters usually contain a metallic filament that warms up to a certain temperature due to the passage of electrical current through it. Quartz or ceramic can be used to cover and protect the filament. Such IR emitters can have standardized energy output values, ranging from 60 to 500 W. To create an IR heating module, those emitters can be attached to a panel. To adjust the maximum IR radiation intensity, the distance between emitters can be adjusted. Power distribution adjustment of these electrical IR heaters is easy and they can provide the required IR radiation in the heating or processing system as demanded by the equipment and process design, however, such IR modules are expensive. Electric IR emitter types include incandescent IR lamps, quartz tubes, reflector type emitters, and resistant elements such as ceramic tubes, and metallic and nonmetallic rods. The energy conversion efficiency of gas-burning IR emitters is around 40%–46% with radiant intensity lower than 22 kWm^{-2}, while the energy conversion efficiency of electrical IR emitters is usually around 78%–85% with a radiant intensity of up to 400 kWm^{-2}. Higher durability and reliability and lower operating cost of propane or natural gas burning IR emitters have made them more suitable for industrial applications, while electric IR emitters have limited application due to their higher capital and operational costs. Gas-burning IR emitters can be categorized into open flame or direct IR emitters and flameless catalytic IR emitters. Normal flame combustion radiates IR by an open flame in direct IR emitters. Visible light may also be emitted as a portion of energy during the combustion process from the fire flame, which can be considered a form of fuel and energy waste. Soot and smoke may also built-up on emitters due to incomplete combustion, which can result in the release of very fine carbon particles into the environment, which is undesirable and should be reduced as much as possible. Therefore, open or direct flame IR emitters have limited applications in food processing due to environmental and safety concerns. A wide range of thermal IR radiation wavelengths in the form of MIR and FIR radiation can be emitted from the catalytic IR emitters without creating any visible flame. The radiation efficiency of the catalytic emitters can vary from 30% to 75% with the radiant intensity ranging from 6 to 28 kWm^{-2}. Such emitters have a heating-up period varying between 180 and 300 s. Aside from the separation distance between the object being IR heated and the IR heater, gas-burning IR emitters' efficiency is also proportional to the IR heater's size. For industrial applications, the gas-burning IR emitters are available in several sizes starting from a few hundred square centimeters. For instance, assuming the emitter is a blackbody, a catalytic IR emitter can emit a peak wavelength of 3.7 μm and with the isothermal surface temperature of the emitter at 500°C the required effective heating area is approximately 900 cm^2 (Pan et al., 2016).

The peak emission range of long-wave FIR emitters is between 3 and 10 μm. These emitters are usually made of ceramic elements consisting of a highly emissive ceramic body containing a Fe–Cr–Al resistant coil. Quartz cassette-style emitters made of translucent quartz tubes built into a polished aluminized steel housing emit shorter peak wavelengths (long to medium wave range). Higher front surface temperatures can be achieved by these emitters. The quartz tungsten IR emitter radiates the shorter end of the medium wave range. This type of emitter contains a star design tungsten coil sealed in a linear clear quartz tube. This type of tungsten coil has low thermal inertia and quick response time. Short-wave halogen IR emitters radiate the shorter end of the spectrum. Their structure is similar to the medium wave tungsten emitters but they contain round tungsten coils with higher temperatures that emit visible light and short wave range IR (WECO News).

3.3 Infrared processing equipment

3.3.1 Infrared thermal processors

Thermal processing destroys trypsin inhibitors and lipoxygenase in soybeans. Kouzeh-Kanani et al. (1983) in a study on IR processing of soybeans used an industrial and laboratory scale procedure on raw dry soybeans that later were used for the production of full-fat soy flour, with the aim to increase its shelf-life and nutritional quality. The IR processing consisted of two stages namely gas-heated IR radiation of soybeans and then holding the IR-heated soybeans in an insulated holding bin to maintain the temperature and complete the thermal processing (Fig. 3.2). In comparison to the conventional method, as the new method did not require a moist preconditioning stage and the final postprocessing dehydration, the production cost of the IR process was significantly lower than the conventional method. Moreover, the results of this study showed that after 1 year of storage the peroxide value of the IR-treated soybean flours was significantly lower than the control sample (Kouzeh-Kanani et al., 1983).

Spices can have high rates of decontamination and conventional decontamination methods can adversely affect their organoleptic quality. Therefore, new decontamination methods are needed to be developed for spices that have minimal deteriorative effects on their quality. In order to find the appropriate decontamination method for spices, different technologies can be compared to help the food industry in selecting the best method. A study investigated simultaneous IR and microwave heating of powdered paprika for microbial decontamination. In order to do so, the performance of microwave and IR in decontamination of powdered paprika that had a natural load of contamination was evaluated. Water activity (aw) was adjusted to 0.88 prior to the heating tests. Microwave and IR heating were used to increase the temperature of powdered paprika to 98°C rapidly, and then the heated paprika powder was kept in a laboratory oven to hold the sample temperature steady at 98°C for a 20 min holding time. In the experimental set-up, the NIR-IR emitters were placed at a 20 cm dis-

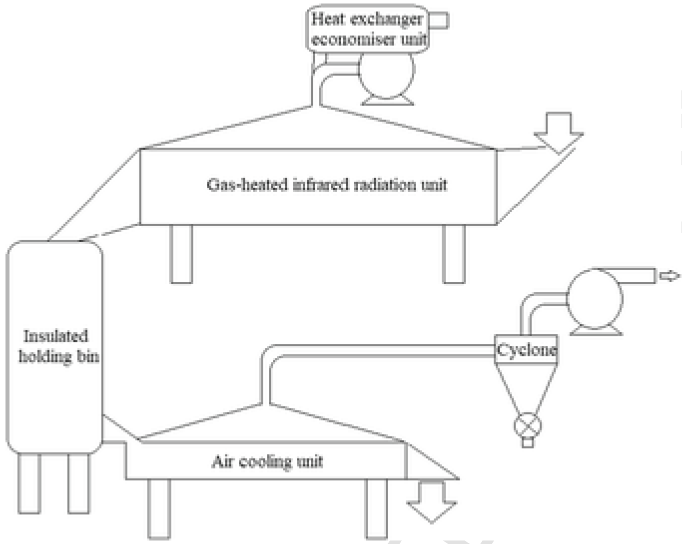

Figure 3.2 Industrial-scale IR processing unit for soybeans.

tance above and below a Petri dish that contained the paprika powder samples. The mesophilic bacteria enumeration of the samples before and after thermal treatment showed that IR heat-up treatment in combination with 20 min holding at 98°C caused a 3.8 log colony forming unit (CFU) reduction in the mesophilic bacteria total number. On the other hand, the microwave heating treatment performance was better to some extent and it showed one log CFU more decrease in the same temperature and holding time. A thermal camera was used to monitor the temperature change pattern in the samples. The study of moisture distribution and temperature profiles of the paprika powder samples during the IR and microwave heating showed that these two heating up methods resulted in different moisture distribution and temperature change patterns in the samples, and this difference was probably the reason why these two heating methods resulted in different amount of decontamination in the samples. This study by comparing the two heating methods showed that in similar processing conditions they result in different amounts of microbial decontamination, which is probably due to different heating mechanisms and initial moisture distribution patterns (Eliasson et al., 2015).

Sakai and Hanzawa (1994) have reviewed the applications of FIR heating in Japan. Because of FIR heating superiority in terms of product quality and costs, this heating method has been adopted for use in various food processing industries, as it has some advantages in comparison with conventional heating (Fig. 3.3). These advantages include uniform heating, high heat transfer efficiency that reduces both energy costs and processing time, high safety and controllability, not heating up the ambient air, the possibility of automation and compact design, and minimal effect of the surface irregularities on the heat transfer rate. However, as the rapid heating rates

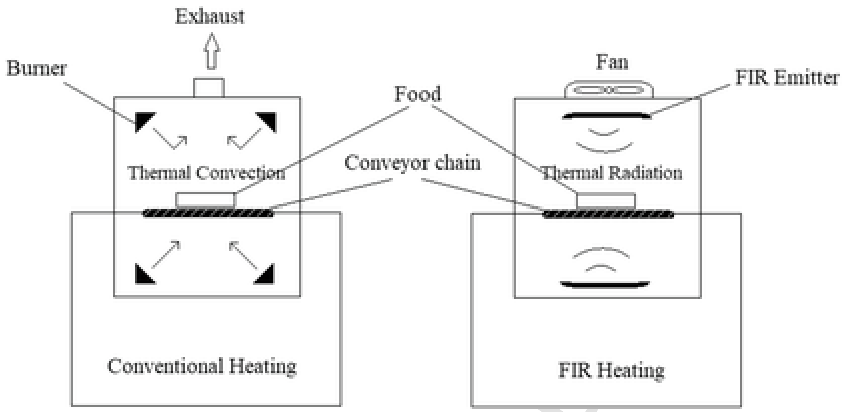

Figure 3.3 Schematic of conventional (*left*) and FIR (*right*) processing apparatus.

can cause overheating, precise condition control is necessary. In the food industry, FIR heating can be used for drying, roasting, pasteurization, baking, and thawing (Sakai and Hanzawa, 1994).

Postharvest heat treatments have become more popular as a method for inhibiting strawberry fungal spoilage during its shelf life. Tanaka et al. (2007) investigated an alternative method for surface decontamination of strawberries by the application of FIR heating. As an alternative to conventional heating methods, FIR radiation heating technology can be used as it can result in contactless and rapid heating. In the study, ANSYS CFX5.7 software was used to perform CFD simulation to evaluate the suitability of the FIR method for surface decontamination. In order to do so, heat transfer simulations, convection-diffusion air flow in combination with Monte Carlo FIR radiation simulations were used. A thermographic camera was used to acquire empirical measurement data, which were then validated against the computation results (Fig. 3.4). Results showed that air convection heating leads to less uniform surface heating than FIR heating, while at the same average temperature, the maximum temperature of the FIR heated samples was always below the critical 50°C limits. However, results showed that in this configuration, depending on the temperature of the used heater, the surface heating rate of the convection air heating (at 0.2 m/s) method was, equal to or higher than the FIR heating method. It was suggested that placing FIR heaters on four sides of the processing chamber in combination with cyclic heating operation can be a better configuration (Tanaka et al., 2007).

3.3.2 Infrared blanchers and dryers

Drying is one of the best preservation methods for agricultural products. The drying process consists of removing water from food and agricultural products. Salehi (2019) reviewed the current and potential applications of IR drying systems for the dehydration of different agricultural products. Delivering thermal energy by IR irradiation is one of the best approaches to reducing the drying time. Various IR drying

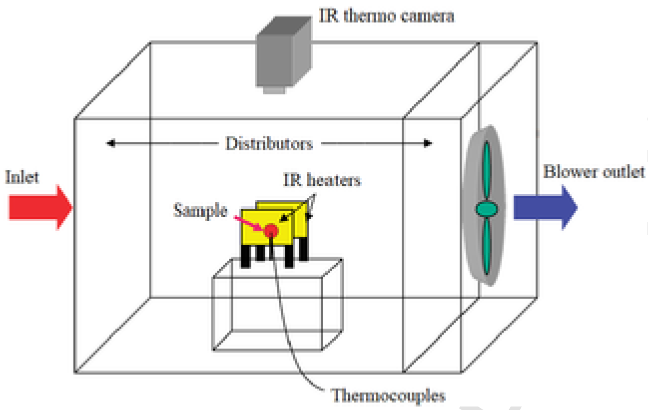

Figure 3.4 Schematic of the experimental IR heating unit for postharvest treatment (Tanaka et al., 2007).

methods were studied for the dehydration of fruits and vegetables. These methods included IR combined with hot air drying, fluidized bed drying, microwave drying, and vacuum drying methods as well as IR-only drying. In the review, drying of mushrooms, onions, garlic, banana, apples, quince, grapefruit, lemon, pumpkin, persimmon, peach, and carrots using different IR or IR combined drying methods were explored and dried products' quality and texture, effective moisture diffusivity, and the drying time, as affected by different IR drying methods were studied. It was concluded that IR heating has several advantages over conventional heating methods. Its advantages include better product quality such as structure and porosity, as well as uniform heating, high heat transfer rate, low processing time, low energy consumption, and high energy efficiency (80%–90%), which lead to low energy costs. Therefore, using IR in the drying process could be a substitute or alternate approach for the conventional blanching and drying methods that can result in high-quality dried products such as fruits and vegetables. They also reviewed suitable mathematical IR drying models (Salehi, 2019).

In another study of IR heating in the drying technology, Shewale and Hebbar (2017) investigated the application of IR in low-humidity air-drying of slices of apples as a pretreatment. Conventional drying technologies cause degradation in the product quality and have a longer processing time. These problems are more observed in hot air drying methods. One of the options for maintaining the product quality of heat-sensitive foods such as fresh fruits is the low-humidity air-drying method. In this study, they investigated the effects of IR and Potassium Metabisulphite pretreatment of apple slices on the low-humidity air-drying process and compared the product quality of this method with freeze-drying and conventional hot air drying. IR pretreatment of the apple slices caused a 17% reduction in the drying time in the hot air drying and a 23% reduction in the low-humidity air-drying time. The physicochemical evaluation of the dried products showed that low-humidity air-dried slices that were treated with IR retained 72%–74% of their total phenolic content and 82%–90% of their ascorbic acid content, these retention values were comparable to the freeze-dried products. In comparison with hot air-dried and freeze-dried products, low-humidity air-dried apple slices had a higher rehydration ratio and lower color change. Moreover, the low-humidity air-drying drying time was nearly 37% shorter than the drying time of the hot air drying method (Shewale and Hebbar, 2017).

In a study, carrot slices were blanched using IR heating and they were then dried using a hybrid IR-assisted hot air dryer, and the performance of the used IR equipment was compared with conventional blanching and drying methods in terms of vitamin C retention, process time, and rehydration properties. Results of this study showed that intermittent IR heating achieved the required enzyme inactivation level heating for 8–15 min at 180–240°C. The absolute moisture content of the carrot samples was reduced from 13% to 23% by IR blanching. This reduction in moisture helped reduce the drying time of the blanched samples by approximately 45% in the hybrid IR-assisted hot air dryer as compared to the hot water blanched samples dried using conventional hot air drying. IR blanching also preserved the cell structure better resulting in a higher rehydration ratio of the dried sample (Vishwanathan et al., 2013). Fig. 3.5 shows the schematics of the IR dry blancher and hybrid IR and hot air dryer. This design can be used for the industrial application of IR in blanching and drying.

Sun-drying as the oldest drying method is a traditional method for the production of dehydrated food products by their exposure to direct sunlight. The sun's IR radiation reduces the moisture content and water activity of the products, thus increasing shelf life without the need for complex packaging materials. Comparisons between convective heating and industrial IR heating have shown that the latter has more advantages. These advantages include shorter processing time, higher heat transfer coefficient, and lower energy consumption. IR processing can be done at ambient air temperature, as the air is transparent to IR radiation. The control of IR processing parameters is relatively easy and the IR heating equipment can be automatic and com-

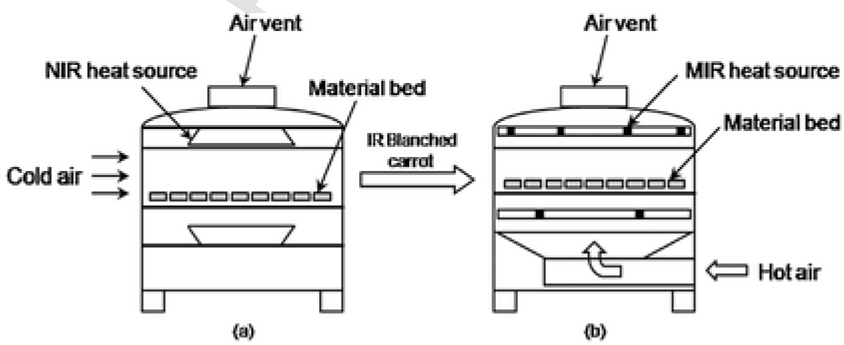

Figure 3.5 Schematics of IR dry blancher (a) and hybrid dryer (b) (Vishwanathan et al., 2013).

pact. Fig. 3.6 shows a schematic of an experimental batch IR-assisted convective dryer that was used to dry apple slices. The dryer is equipped with nine 175 W glass IR lamps, with a peak wavelength of 1200 nm. The distance between the lamps and the sample can be adjusted between 0.1 and 0.4 m. Samples were placed on a wire tray, which was sited on a balance to monitor the weight change. Electric heaters with 5.8 kW total power and air baffles were installed in the duct connected to the IR chamber. To ensure uniform airflow, IR lamps were separated from the sample area using quartz glass. Computers connected to K-type thermocouples and an anemometer were used to measure and record the temperature and air speed respectively (Nowak and Lewicki, 2004).

Kumar et al. (2005) investigated the drying of onion slices using a combination of hot-air and IR heating methods, and the characteristics of onion slices as affected by processing parameters such as air velocity and temperature, slice thickness, and drying temperature, were investigated. The quality of dried onion slices was evaluated by their pyruvic acid content and color. Pyruvic acid content is used as a flavor indicator. Amongst the tested samples, 2-mm-thick onion slices that were dried at the low drying temperature of 60°C with 2 m/s air velocity and 40°C air temperature, had the best color and flavor retention. The drying process variables were correlated to the moisture content of the onion slice by an empirical equation, which showed a good fit with the acquired data. Another equation was developed to correlate the pyruvic acid content with the drying process condition and the processing time, which also showed a very good fit. On the other hand, the equations developed to fit the onion slices' total color change with the process parameters, demonstrated a lower but acceptable fit ($R^2 = 0.86$). Overall the combination of IR with other drying

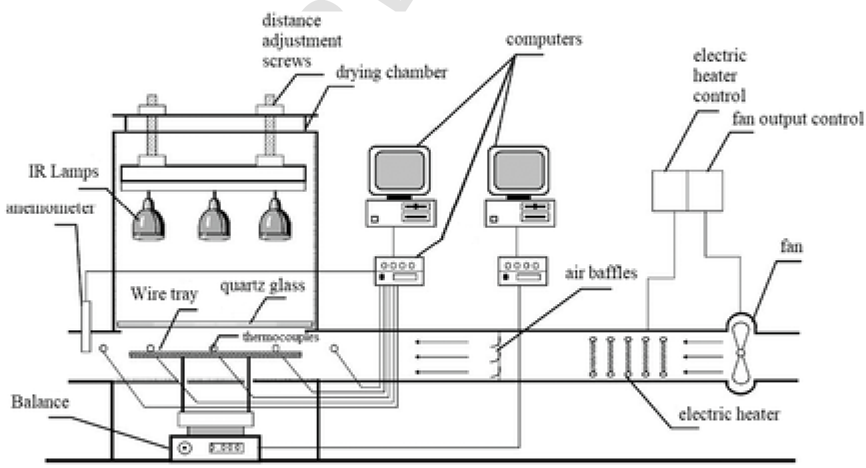

Figure 3.6 Schematic of an batch infrared (IR) assisted convective dryer (Nowak and Lewicki, 2004).

methods in comparison with each individual method resulted in shorter drying time and better onion slice quality (Kumar et al., 2005).

3.3.3 Infrared peeling

The vegetable and fruit processing industry currently use steam peeling and hot lye peeling techniques. Steam-peeled products quality is usually low product and lye peeling cause a lot of alkaline wastewater that are the major disadvantage of these peeling methods. High heat penetration depth in the abovementioned methods is undesirable. Therefore, IR with its low penetration depth and high heat transfer rate is an ideal heating method for peeling vegetables and fruits by loosening their skin. IR peeling can be classified as a dry-peeling method as it does not require a heating medium to transfer the thermal energy to the product, which in the aforementioned methods is water or steam. A study used a combination of IR heating and caustic soda as a dry-caustic peeling for peaches and, white potatoes and it was reported that this combined peeling method could lead to significant reductions in the consumption of caustic soda, wastewater generation, and peeling loss. Moreover, this method was also investigated for tomato IR dry-peeling performance as affected by various factors such as different tomato cultivars' physical properties. Results have shown that using this method for tomatoes can improve the quality of peeled products as well as peeling performance. Moreover, the peeling loss in this method was lower than in the lye peeling and steam peeling methods. Furthermore, a study of the performance of pilot-scale IR dry-peelers utilizing electric emitters that were used by two tomato processors showed promising results. Thus the application of IR peeling technology is being expanded to other vegetables and fruits and optimization studies on this technology are ongoing (McHugh and Pan, 2015).

3.3.4 Infrared baking

Another application of IR heating is in assisting the baking process. Demirkesen et al. (2011) investigated the optimization of IR-assisted microwave baking of formulations of chestnut–rice bread. They used halogen lamps as the IR source. They wanted to study gluten-free bread formulation design using rice and chestnut flour, adding a mixture of guar gum and xanthan, and then baking them using a combination IR-assisted microwave oven. In order to optimize the formulation and process of gluten-free bread production, they used response surface methodology (RSM). Various amounts of emulsifiers and different percentages of chestnut flour were added to rice flour to create different gluten-free bread formulations. The prepared formulations were then baked using different baking times, microwave powers, and IR powers. The baking time range was between 9 and 17 min, the microwave power levels ranged between 30% and 70%, and the IR power range was 40%–80%. To evaluate the quality of the produced bread, color change, specific volume, firmness, and weight loss, of them were measured. To make comparisons, regular wheat bread and gluten-free bread were also baked using a conventional oven. Results showed that the best quality of gluten-free bread was produced using 30% microwave power combined with 40% IR power and baked for 9 min, and the best formulation for this process was the one that contained 46.5% chestnut flour and 0.62% emulsifier. The quality of such gluten-free bread was comparable to conventionally baked bread (Demirkesen et al., 2011).

3.4 Optimization of infrared processing

Lao et al. (2019) reviewed the main applications and development trends of efficient IR processing methods for plant foods. The IR heating process has the potential to be highly efficient energy-conserving technology. However, the application of these technologies is at the early stage of industrial use in food technology. In comparison to conventional heating, the IR heating method has noticeable benefits. These benefits include shorter processing time and uniform heating while causing lower quality degradation. Nevertheless, IR processing also has some limitations such as low penetration depth; therefore, it is not suitable for heating thick or large pieces of food. The purpose of optimization of IR processing methods is to reduce these limitations and increase the utilization of the aforementioned advantages to produce high-quality foods efficiently. In the review, different types of IR emitters and IR processing parameters as well as the combination of IR heating methods with other heating methods mostly in drying were investigated. Other applications such as IR blanching, IR pasteurization, and disinfestation were also investigated. They concluded that in order to develop efficient IR processing technology parameters such as processing device size, energy utilization, and carbon emission as well as product's nutritional and sensory parameters should be considered to optimize the operating conditions (Lao et al., 2019).

IR combined with microwave and hot air heating of foods was investigated in another study with the aim to optimize the control of moist foods' surface moisture. In order to do so, moisture and temperature profiles of the foods as heated by microwave combined with hot air and IR were studied using a model porous multiphase media for the study of moisture and heat transfer. Surface moisture build-up was observed in microwave heating without IR or hot air combination. This phenomenon occurred due to pressure-driven enhanced moisture flow to the model food surface and the inability of the cold ambient air that was removing the moisture from the model food at a high rate. Similarly, in the case of some foods that IR waves can penetrate deeply, a combination of the heating method with IR can also lead to the build-up of surface moisture. Whereas for foods that have high surface absorbance for IR, the combination of other heating methods with IR can lead to reduced surface moisture. In this case, if the power level threshold grows higher than a certain level, it can reduce the moisture at the surface to a lower value than its initial value. A combination with hot air will lead to a surface temperature increase and can also reduce the moisture at the surface. However, such a combination with hot air is not as effective as the combination with IR heating. This is probably due to the fact that the IR irradiation will cause a much higher surface heat flux as compared to hot air. Accumulated moisture at the surface can also be eliminated by increasing heat and mass transfer coefficients, which can be achieved by increasing the air velocity (Datta and Ni, 2002).

3.5 Conclusion

IR heating is a relatively novel heating method that is radiated from devices called emitters. Different types of IR emitters, IR heating methods, and their applications in the food industry were discussed. IR heating can be used solely or in combination with conventional and novel processing technologies to improve processes such as blanching, thawing, drying, cooking, baking, and roasting. This heating technology has high thermal energy delivery efficiency, faster and uniform heating, and shorter processing time, which leads to lower energy consumption. IR heating can be combined with other processing technologies that can help to maintain product quality and reduce processing time. Although several researchers have studied different applications of IR heating that are summarized in this chapter, in order to improve the industrial feasibility of the use of IR processing, more research in this area is necessary.

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